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Interpretation of Low-Temperature Data Part VI:

The Magnetite Verwey Transition

(Part C): Low-Temperature Demagnetization of Stoichiometric Magnetite

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In this installment of the ongoing IRM Quarterly *series on low-temperature magnetism, we return for a third time to the Verwey transition in stoichiometric magnetite. The first magnetite article* (IRM Quarterly, v. 20, *n. 4, 2011) provided an overview and focused on the physical nature of the transition. The second article* (IRM Quarterly, v. 21*, n. 4, 2011*) *discussed the effects on remanence, susceptibility, and hysteresis of cooling in an applied field across the Verwey transition, in both the single domain and multi-domain case. The so-called field-cooled (FC) / zero-field-cooled (ZFC) experiment is a common one performed at the* IRM, *and we discussed the interpretation of FC/ZFC data. In this article we address the Verwey transition in the context of another common experiment performed at the* IRM: *low-temperature demagnetization of a remanence acquired at room-temperature. We again restrict our discussion to stoichiometric magnetite, leaving cation substitution, oxidation, stress, and pressure effects for future articles in this seemingly inexhaustible series.*

Introduction

Low-temperature demagnetization (LTD) of magnetite (by cycling a sample from room temperature to a temperature T<T_V~122K and back, in zero field) has a long and distinguished history (e.g., Ozima et al., 1964; Kobayashi & Fuller, 1968; Merrill, 1970). Despite many years of study, however, LTD still retains some significant mysteries. In contrast to the warming of low-temperature remanences (*IRMQ v. 21* n. 4), where properties change abruptly and dramatically when the strong monoclinic magnetocrystalline anisotropy vanishes at T_V, the changes on cooling from room temperature can be more gradual, subtle and complex: the weak cubic magnetocrystalline anisotropy diminishes progressively until the easy axis orientation changes at the isotropic point T_K~130K (from body diagonal to cube edge), and finally the monoclinic phase nucleates at T_V and propagates through the individual particles. Moreover, the initial state for LTD experiments is often subtle and complex as well (natural remanence, or weak-field lab analogues), whereas FC/ZFC experiments typically involve brute-force strong-field remanences. For these reasons, the behavior we observe during zero-field cooling and rewarming can exhibit a rich variety of features.

For many years there were practical hurdles to measuring magnetization during complete cooling/warming cycles. Commonly the effects of low-T cycling were studied solely through measurement of remanence at room temperature, before and after treatment by immersion in liquid nitrogen in a zero-field environment (e.g., Merrill, 1970). Some of the key early observations of magnetization during cooling/warming cycles (Yama-ai et al., 1963; Nagata et al., 1964; Ozima et al., 1964; Kobayashi & Fuller, 1968) involved the newly-developed vibrating-sample magnetometer (Flanders and Doyle, 1962). Later work involved continuous measurements on specialized instruments including a Dewar-equipped spinner magnetometer (Hartstra, 1983) and a SQUID susceptometer (Halgedahl & Jarrard, 1995). At the *IRM*, however, the workhorse Quantum Designs MPMS instruments were unable to measure during cooling, due to hardware and software limitations, until about 1998 (*IRMQ v. 8*, n. 4; Özdemir & Dunlop, 1999). Prior to that all low-T experiments at the IRM were based solely on measurements during warming, and it has only been over the last decade or so that we have accumulated a large body of data on the behavior of magnetite-bearing materials during complete low-T cycles (e.g., Fig 1).

Pioneering Studies

The earliest studies of changes in room-temperature remanence during low-T cycles were designed to understand (a) the fundamental origins of stable remanence in multidomain grains and the relative importance of stress, microstructures, magnetocrystalline anisotropy and particle geometry, and (b) the nature of the low-temperature

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Visiting Fellow's Reports

How does magnetization vary in the lower crust? Rock magnetic studies from the Athabasca Granulite Terrain, Canada

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Introduction: SWARM, a trio of satellites observing the Earth's magnetic field with a launch date of 2011, will provide detailed information on the magnetization of the Earth's crust and the long wavelength magnetic anomalies (LWMA) produced there. Although not the only mission of SWARM, mapping of lithospheric magnetization and the resulting geologic interpretation is an important part of this immense project. The last large collection of satellite magnetic data, the MAGSAT project in the early 1980s, provided information on magnetic anomalies of crustal source of some +/- 15 nT. Interpretation of these anomalies required 2 to 5 A/m of magnetization in lower crustal rocks, but studies did not find sufficient susceptibility or magnetization in the lower crust (Shive et al., 1992). Much is known about the magnetic properties of the crust (Purucker and Whaler, 2007), but we still do not fully understand what is magnetic in the lower crust and what is the source of the LWMA. Early studies only considered susceptibility and induced magnetization; remanence was not considered as a possible contributor.

The Athabasca Granulite Terrane, between the Proterozoic Rae and Hearne Blocks of the Churchill Province of north-central Canada is an excellent region to study the rock magnetic properties of lower crustal rocks. It is the largest exposure of lower crustal rocks on the Earth's surface, composed of suites of both felsic and mafic granulite facies rocks metamorphosed at ca 1.0 GPa pressure. They have resided in the deep crust at depths of ~35 km from ~2.6 Ga to ~1.8 Ga when they were exhumed (Williams and Hanmer, 2006). Exposed rocks include tonalite, granite, felsic granulite, mafic granulite, and mafic dikes. Extensive geologic information is available from Mike Williams (UMass), colleagues and students (e.g. Dumond et al., 2008; Flowers et al., 2008). Aeromagnetic coverage of this region is excellent, and the resulting anomaly map is quite exquisite (Fig. 1), showing some direct relationships between rock type and anomalies and other examples where anomalies cut across mapped units.

What I did at the IRM: A total of forty-two samples representing all major rock types in the area, and coming from both magnetic high and low regions were brought to the IRM to augment initial susceptibility and NRM measurements. Room temperature hysteresis on all samples revealed a wide range of properties, with M_r/M_s ranging from 0.01 to 0.9 and H_{cr}/H_c ranging from 1.2 to 13.4. Samples from the negative anomaly areas generally plot with H_{cr}/H_c less than 4.0 indicating PSD

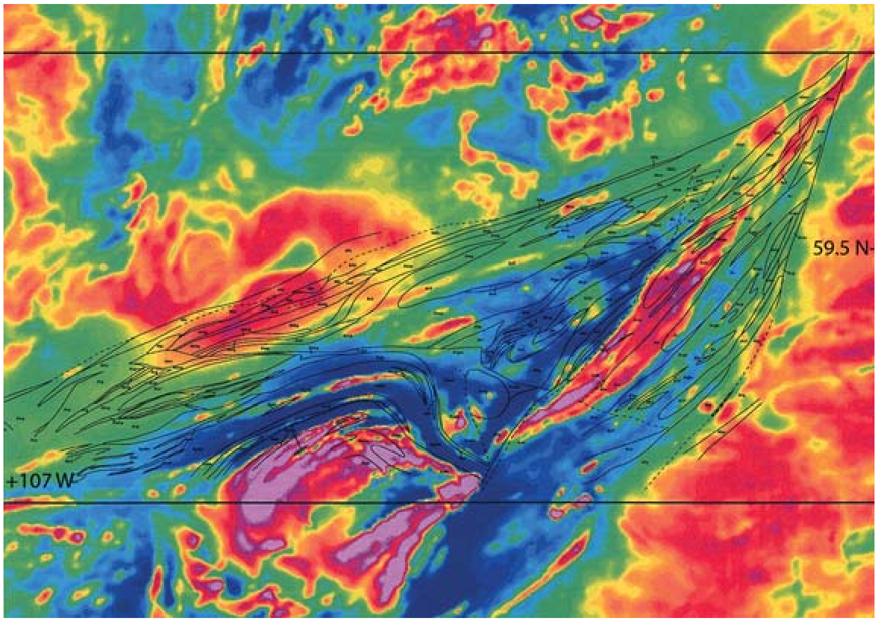


Figure 1. Aeromagnetic anomaly map of a section of the Athabasca granulite terrain, northern Saskatchewan, Canada, with geologic contacts overlain. Data from the Geological Survey of Canada, map processed by C. Koteas, UMass. Total anomaly range ≈2000 nT. Width of map area ≈100 km. (see full-color version at http://www.irm.umn.edu/quarterly/irmq22-2.pdf).

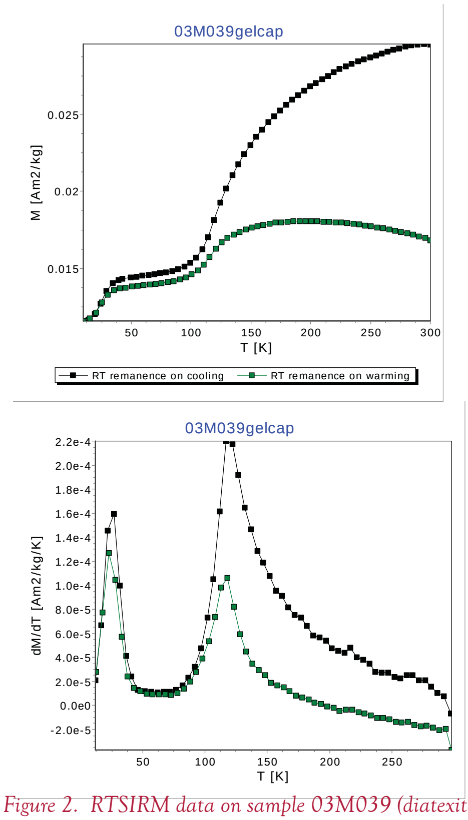


Figure 2. RTSIRM data on sample 03M039 (diatexite from magnetic high region), showing presence of both magnetite and pyrrhotite. Upper plot - magnetization recorded with temperature; lower plot – first derivative of the above data.

to SD behavior, while most of the samples from the positive anomalies areas plot in the MD range. It should be noted that for a number of samples the actual values of M_r and M_s were very low and loops were not always well defined, indicating the dominance of paramagnetic behavior in these samples. The majority of well-defined loops indicated magnetite as the primary oxide. Despite extensive investigation, no samples have yet produced “fat” loops indicative of hematite or hemo-ilmenite as the predominant oxide mineral.

Investigations of sample behavior at low temperatures using the MPMS system provided interesting although sometimes confusing results. A number of samples, especially those from the tonalite, showed clean and distinct Verwey transitions, as expected for magnetite-dominated rocks; in some samples pyrrhotite is also evident with a drop in magnetization around 30-35°K (Fig. 2). Additional samples produced a Verwey transition, but one of a broad nature extending well over 50° and often with two distinct peaks. A few samples showed only pyrrhotite signatures on heating and cooling. And, sadly enough, a number of samples had little or no indication of diagnostic magnetic behavior during the MPMS runs, indicative of the paramagnetic nature of some of these samples. This behavior was most noticeable in the dike samples, already known to have low susceptibilities ($<10^{-3}$ SI) and weak magnetizations.

The simplest conclusion of this experimental work at IRM is that the rocks in the Athabasca Granulite Terrain include samples with well-behaved magnetite but also samples with little or no magnetite, leading to the observation that the extreme magnetic anomalies are related to large swatches of juxtaposed “magnetic” and “non-magnetic” lower crustal rocks, even though many of them have similar rock descriptions. Work is continuing to investigate specific rock compositions, magnetic properties, and geologic histories to better understand what is magnetic in this part of the lower crust.

References

Dumond, G., McLean, N., Williams, M. L., Jercinovic, M. J., and Bowring, S. A., High resolution dating of granite petrogenesis and deformation in a lower crustal shear zone: Athabasca granulite terrane, western Canadian shield, Chem. Geol., 254, 175-196, 2008.

Flowers, R. M., Bowring, S. A., Mahan, K. H., Williams, M. L., and Williams, I. S., Stabilization and reactivation of cratonic lithosphere from the lower crustal record in the western Canadian shield, Contrib. Mineral. Petrol., 156, 529-549, 2008.

Purucker, M. and Whaler, K., Crustal magnetism, in: Treatise on Geophysics, v. 5, ed. M. Kono, Elsevier, 195-235, 2007.

Shive, P. N., Blakely, R. J., Frost, B. R., and Fountain, D. M., Magnetic properties of the lower continental crust, in: Continental Lower Crust, ed. By Fountain, D. M., Arculus, R., and Kay, R. W., Elsevier, Amsterdam, 145-177, 1992.

Williams, M. L., and Hanmer, S., Structural and metamorphic processes in the Lower Crust: Evidence from the East Athabasca Triangle, Canada, a deep-crystal isobarically cooled terrane, in: Brown, M. and Rusmer, T., Eds., Evolution and Differentiation of the Continental Crust, Cambridge Univ. Press, p. 231-267, 2006.

Visiting Fellows

July - December, 2012

Trevor Almeida
Imperial College London
Characterisation of glass-ceramic samples of magnetite and titanomagnetite

Mitch Campion*
Concordia College
Magnetic investigation of e-Fe2O3 formed after maghemite thermal treatment

Stephen Garrett*
Texas State University-San Marcos
Geomagnetic Study of Burned Rocks at the Gault Site (41BL323), Central Texas

Sara Gillooly
University of Pittsburgh
Validating tree leaf use as a novel method to reduce exposure misclassification

Plinio Jaqueto
University of São Paulo
Earth’s magnetic field variations in the past millennia from Brazilian speleothems

Mathilde Meijers
University of Nice-Sophia Antipolis
Characterizing rock magnetic behavior of remagnetized Paleozoic limestones from the South Armenian Block (Lesser Caucasus) and the central Taurides (southern Turkey)

Gary Stinchcomb
Baylor University
Climatic, geomorphic and human controls on the magnetic properties of soil along the middle Delaware River valley, USA

*U.S. Student Fellows

The next Visiting Fellowship application deadline is October 30.

Magnets Everywhere:

Oncorynchus mykiss

Ficus benjamina

Krafla lava ropes

(images from Wikimedia Commons)

Current Articles

A list of current research articles dealing with various topics in the physics and chemistry of magnetism is a regular feature of the IRM Quarterly. Articles published in familiar geology and geophysics journals are included; special emphasis is given to current articles from physics, chemistry, and materials-science journals. Most abstracts are taken from INSPEC (© Institution of Electrical Engineers), Geophysical Abstracts in Press (© American Geophysical Union), and The Earth and Planetary Express (© Elsevier Science Publishers, B.V.), after which they are subjected to Procrustean culling for this newsletter. An extensive reference list of articles (primarily about rock magnetism, the physics and chemistry of magnetism, and some paleomagnetism) is continually updated at the IRM. This list, with more than 10,000 references, is available free of charge. Your contributions both to the list and to the Current Articles section of the IRM Quarterly are always welcome.

Anisotropy and Magnetic Fabrics

Fanjat, G., V. Shcherbakov, and P. Camps (2012), Influence of magnetic interactions on the anisotropy of magnetic susceptibility: the case of single domain particles packed in globule aggregates, *Studia Geophysica et Geodaetica, 56(3)*, 751-768

Mendes, M., and L. Lagoeiro (2012), Microstructures, crystallographic fabric development and deformation mechanisms in natural hematite aggregates deformed under varied metamorphic conditions, *Journal of Structural Geology, 40,* 29-43

Urrutia-Fucugauchi, J., M. Delgadillo-Peralta, L. Perez-Cruz, and M. Velasco-Villarreal (2012), Heating-induced changes in the anisotropy of magnetic susceptibility of impact breccias, Chicxulub Crater (Mexico), *Studia Geophysica et Geodaetica, 56(3)*, 769-787

Yokoyama, E., R. I. F. Trindade, C. Lana, C. R. Souza, D. Baratoux, Y. R. Marangoni, and E. Tohver (2012), Magnetic fabric of Araguainha complex impact structure (Central Brazil): Implications for deformation mechanisms and central uplift formation, *Earth and Planetary Science Letters, 331*, 347-359

Archeomagnetism

Aidona, E., and D. Kondopoulou (2012), First archaeomagnetic results and dating of Neolithic structures in northern Greece, *Studia Geophysica et Geodaetica, 56(3),* 827-844

Chlupacova, M., F. Hrouda, D. Niznansky, V. Prochazka, Z. Petakova, and F. Laufek (2012), Frequency-dependent susceptibility and other magnetic properties of Celtic and Mediaeval graphitic pottery from Bohemia: an introductory study, S*tudia Geophysica et Geodaetica, 56(3)*, 803-825

Donadini, F. (2012), Combining an archaeomagnetic and radiocarbon study: dating of medieval fireplaces at the Muhlegasse, Zurich, *Journal of Archaeological Science, 39(7)*, 2153-2166

Bio(geo)magnetism

Eder, S. H. K., H. Cadiou, A. Muhamad, P. A. McNaughton, J. L. Kirschvink, and M. Winklhofer (2012), Magnetic characterization of isolated candidate vertebrate magnetoreceptor cells, *Proceedings of the National Academy of Sciences of the United States of America, 109(30),* 12022-12027

Freire, R. (2012), Conditioned response to a magnetic anomaly in the Pekin duck (Anas platyrhynchos domestica) involves the trigeminal nerve, *Journal of Experimental Biology, 215(14),* 2399-2404

Hellinger, J., and K. P. Hoffmann (2012), Magnetic field perception in the rainbow trout Oncorynchus mykiss: magnetite mediated, light dependent or both?, *Journal of Comparative Physiology A-Neuroethology Sensory Neural and Behavioral Physiology, 198(8)*, 593-605

Larrasoana, J. C., A. P. Roberts, L. Chang, S. A. Schellenberg, J. D. F. Gerald, R. D. Norris, and J. C. Zachos (2012), Magnetotactic bacterial response to Antarctic dust supply during the Palaeocene-Eocene thermal maximum, *Earth and Planetary Science Letters, 333*, 122-133

Toner, B. M., Berquo, T. S., Michel, F. M., Sorensen, J. V., Templeton, A. S., and Edwards, K. J., 2012. Mineralogy of iron microbial mats from Loihi Seamount. *Frontiers in Microbiological Chemistry 3*, 1-18.

Valkova, T., and M. Vacha (2012), How do honeybees use their magnetic compass? Can they see the North?, *Bulletin of Entomological Research, 102(4),* 461-467

Environmental Magnetism and Paleoclimate Proxies

Lascu, I., K. K. McLauchlan, A. Myrbo, P. R. Leavitt, and S. K. Banerjee (2012), Sediment-magnetic evidence for last millennium drought conditions at the prairie-forest ecotone of northern United States, *Palaeogeography Palaeoclimatology Palaeoecology, 337*, 99-107, doi: 10.1016/j.palaeo.2012.04.001.

Reyes, B. A., R. C. Ruiz, J. Martinez-Cruz, F. Bautista, A. Goguitchaichvili, C. Carvallo, and J. Morales (2012), Ficus benjamina leaves as indicator of atmospheric pollution: a reconaissance study, *Studia Geophysica et Geodaetica, 56(3)*, 879-887

Rijal, M. L., K. Porsch, E. Appel, and A. Kappler (2012), Magnetic signature of hydrocarbon-contaminated soils and sediments at the former oil field Hanigsen, Germany, *Studia Geophysica et Geodaetica, 56(3)*, 889-908

Simkins, L. M., A. R. Simms, A. M. Cruse, T. Troiani, E. A. Atekwana, J. Puckette, and Y. Yokoyama (2012), Correlation of early and mid-Holocene events using magnetic susceptibility in estuarine cores from bays along the northwestern Gulf of Mexico, *Palaeogeography Palaeoclimatology Palaeoecology, 346*, 95-107

Extraterrestrial Magnetism

Carley, R. A., K. A. Whaler, M. E. Purucker, and J. S. Halekas (2012), Magnetization of the lunar crust, *Journal of Geophysical Research-Planets, 117(E08001)*, doi: 10.1029/2011JE003944..

Cournede, C., J. Gattacceca, and P. Rochette (2012), Magnetic study of large Apollo samples: Possible evidence for an ancient centered dipolar field on the Moon, *Earth and Planetary Science Letters, 331*, 31-42

Dehouck, E., V. Chevrier, A. Gaudin, N. Mangold, P. E. Mathe, and P. Rochette (2012), Evaluating the role of sulfide-weathering in the formation of sulfates or carbonates on Mars, *Geochimica Et Cosmochimica Acta, 90*, 47-63

Uehara, M., J. Gattacceca, P. Rochette, F. Demory, and E. M. Valenzuela (2012), Magnetic study of meteorites recovered in the Atacama desert (Chile): Implications for meteorite paleomagnetism and the stability of hot desert surfaces, *Physics of the Earth and Planetary Interiors, 200*, 113-123, doi: 10.1016/j.pepi.2012.04.007.

Geomagnetism and Geodynamo Studies

Biggin, A. J., B. Steinberger, J. Aubert, N. Suttie, R. Holme, T. H. Torsvik, D. G. van der Meer, and D. J. J. van Hinsbergen (2012), Possible links between long-term geomagnetic variations and whole-mantle convection processes, *Nature Geoscience, 5(8)*, 526-533

Huguet, L., and H. Amit (2012), Magnetic energy transfer at the top of the Earth's core, *Geophysical Journal International, 190(2)*, 856-870

Olson, P., and R. Deguen (2012), Eccentricity of the geomagnetic dipole caused by lopsided inner core growth, *Nature Geoscience, 5(8)*, 565-569

Magnetic Field Records and Paleointensity Methods

Bourne, M., C. Mac Niocaill, A. L. Thomas, M. F. Knudsen, and G. M. Henderson (2012), Rapid directional changes associated with a 6.5 kyr-long Blake geomagnetic excursion at the Blake-Bahama Outer Ridge, *Earth and Planetary Science Letters, 333*, 21-34

Di Chiara, A., F. Speranza, and M. Porreca (2012), Paleomagnetic secular variation at the Azores during the last 3 ka, *Journal of Geophysical Research-Solid Earth, 117(B07101)*, doi: 10.1029/2012JB009285.

Jin, C. S., Q. S. Liu, and J. C. Larrasoana (2012), A precursor to the Matuyama-Brunhes reversal in Chinese loess and its palaeomagnetic and stratigraphic significance, *Geophysical Journal International, 190(2)*, 829-842

Liebke, U., E. Appel, U. Neumann, and L. Ding (2012), Dual polarity directions in basaltic-andesitic dykes - reversal record or self-reversed magnetization?, *Geophysical Journal International, 190(2)*, 887-899

Yu, Y. (2012), High-fidelity paleointensity determination from historic volcanoes in Japan, *Journal of Geophysical Research-Solid Earth, 117(B08101)*, doi: 10.1029/2012JB009368

Mineral Physics and Chemistry

Echigo, T., D. M. Aruguete, M. Murayama, and M. F. Hochella (2012), Influence of size, morphology, surface structure, and aggregation state on reductive dissolution of hematite nanoparticles with ascorbic acid, *Geochimica Et Cosmochimica Acta, 90*, 149-162

French, R. A., M. A. Caraballo, B. Kim, J. D. Rimstidt, M. Murayama, and M. F. Hochella (2012), The enigmatic iron oxyhydroxysulfate nanomineral schwertmannite: Morphology, structure, and composition, *American Mineralogist, 97(8-9)*, 1469-1482

Garcia, J., and G. Subias (2012), Comment on "Direct Observation of Charge Ordering in Magnetite Using Resonant Multiwave X-Ray Diffraction", *Physical Review Letters, 109(049701)*, doi: 10.1103/PhysRevLett.109.049701..

Jacobsen, H. (2012), Temperature dependence of the magnetization of canted spin structures, *Journal of Magnetism and Magnetic Materials, 324(19)*, 3218-3222

Kovalevsky, A. V., E. N. Naumovich, A. A. Yaremchenko, and J. R. Frade (2012), High-temperature conductivity, stability and redox properties of $Fe_{3-x}Al_xO_4$ spinel-type materials, *Journal of the European Ceramic Society, 32(12)*, 3255-3263

Larese-Casanova, P., A. Kappler, and S. B. Haderlein (2012), Heterogeneous oxidation of Fe(II) on iron oxides in aqueous systems: Identification and controls of Fe(III) product formation, *Geochimica Et Cosmochimica Acta, 91*, 171-186

Lilova, K. I., C. I. Pearce, C. Gorski, K. M. Rosso, and A. Navrotsky (2012), Thermodynamics of the magnetite-ulvospinel (Fe_3O_4-Fe_2TiO_4) solid solution, *American Mineralogist, 97(8-9)*, 1330-1338

Okudera, H., A. Yoshiasa, K. Murai, M. Okube, T. Takeda, and S. Kikkawa (2012), Local structure of magnetite and maghemite and chemical shift in Fe K-edge XANES, *Journal of Mineralogical and Petrological Sciences, 107(3)*, 127-132

Raghuwanshi, V. S., D. Tatchev, S. Haas, R. Harizanova, I. Gugov, C. Russel, and A. Hoell (2012), Structural analysis of magnetic nanocrystals embedded in silicate glasses by anomalous small-angle X-ray scattering, *Journal of Applied Crystallography, 45*, 644-651

Rock and Mineral Magnetism

Brown, L. L., and S. A. McEnroe (2012), Paleomagnetism and magnetic mineralogy of Grenville metamorphic and igneous rocks, Adirondack Highlands, USA, *Precambrian Research, 212*, 57-74

Chou, Y. M., S. R. Song, C. Aubourg, Y. F. Song, A. M. Boullier, T. Q. Lee, M. Evans, E. C. Yeh, and Y. M. Chen (2012), Pyrite alteration and neoformed magnetic minerals in the fault zone of the Chi-Chi earthquake (M-w 7.6, 1999): Evidence for frictional heating and co-seismic fluids, *Geochemistry Geophysics Geosystems, 13(Q08002)*, doi: 10.1029/2012GC004120.

Da Silva, A. C., M. J. Dekkers, C. Mabille, and F. Boulvain (2012), Magnetic susceptibility and its relationship with paleoenvironments, diagenesis and remagnetization: examples from the Devonian carbonates of Belgium, *Studia Geophysica et Geodaetica, 56(3)*, 677-704

de Montferrand, C. (2012), Size-Dependent Nonlinear Weak-Field Magnetic Behavior of Maghemite, *Small, 8(12)*, 1945-1956

Ferre, E. C., K. J. Michelsen, W. G. Ernst, J. D. Boyd, and E. Canon-Tapia (2012), Vertical zonation of the Barcroft granodiorite, White Mountains, California: Implications for magmatic processes, *American Mineralogist, 97(7)*, 1049-1059

Horng, C. S., C. A. Huh, K. H. Chen, C. H. Lin, K. S. Shea, and K. H. Hsiung (2012), Pyrrhotite as a tracer for denudation of the Taiwan orogen, *Geochemistry Geophysics Geosystems, 13(Q08z47)*, doi: 10.1029/2012GC004195.

Kars, M., C. Aubourg, J. P. Pozzi, and D. Janots (2012), Continuous production of nanosized magnetite through low grade burial, *Geochemistry Geophysics Geosystems, 13(Q08z48)*, doi: 10.1029/2012GC004104.

Kasama, T., R. J. Harrison, N. S. Church, M. Nagao, J. M. Feinberg, and R. E. Dunin-Borkowski (2012), Ferrimagnetic/ferroelastic domain interactions in magnetite below the Verwey transition. Part 1: Electron Holography and Lorentz Microscopy, *Phase Transitions: A Multinational Journal*, doi: 10.1080/01411594.2012.695373.

Lattard, D., U. Sauerzapf, and A. Kontny (2012), Rapid surficial oxidation of synthetic Fe-Ti oxides at high temperature: Observations and consequences for magnetic measurements, *Geochemistry Geophysics Geosystems, 13(Q08z46)*, doi: 10.1029/2012GC004152.

Liu, Q. S., B. R. Frost, H. C. Wang, J. P. Zheng, Q. L. Zeng, and Z. M. Jin (2012), Magnetic petrology of high Fe-Ti eclogites from the CCSD main hole: Implications for subduction-zone magnetism, *Journal of Geophysical Research-Solid Earth, 117(B07102)*, doi: 10.1029/2011JB008621..

Oliva-Urcia, B., and A. Kontny (2012), Remanent magnetization of maghemitized basalts from Krafla drill cores, NE-Iceland, *Studia Geophysica et Geodaetica, 56(3)*, 641-657

Zhang, C. X., G. A. Paterson, and Q. S. Liu (2012), A new mechanism for the magnetic enhancement of hematite during heating: the role of clay minerals, *Studia Geophysica et Geodaetica, 56(3)*, 845-860

Tectonics/Paleomagnetism

Oliva-Urcia, B., A. M. Casas, E. L. Pueyo, and A. Pocovi-Juan (2012), Structural and paleomagnetic evidence for non-rotational kinematics of the South Pyrenean Frontal Thrust at the western termination of the External Sierras (southwestern central Pyrenees), *Geologica Acta, 10(2)*, 125-144

Ruiz-Martinez, V. C., T. H. Torsvik, D. J. J. van Hinsbergen, and C. Gaina (2012), Earth at 200 Ma: Global palaeogeography refined from CAMP palaeomagnetic data, *Earth and Planetary Science Letters, 331*, 67-79

Chronostratigraphy/Magnetostratigraphy

Barendregt, R. W., R. J. Enkin, and D. L. Tessler (2012), Magnetostratigraphy of late neogene glacial, interglacial, and preglacial sediments in the Saskatoon and Regina areas, Saskatchewan, Canada, *Studia Geophysica et Geodaetica, 56(3)*, 705-724

Brink, J. S., A. I. R. Herries, J. Moggi-Cecchi, J. A. J. Gowlett, C. B. Bousman, J. Hancox, R. Grün, V. Eisenmann, and L. Rossouw (2012), First hominine remains from a 1.07-0.99 Ma hyaena accumulation at Cornelia-Uitzoek, Free State Province, South Africa, *Journal of Human Evolution*, doi: 10.1016/j.jhevol.2012.06.004.

Dallanave, E., C. Agnini, G. Muttoni, and D. Rio (2012), Paleocene magneto-biostratigraphy and climate-controlled rock magnetism from the Belluno Basin, Tethys Ocean, Italy, *Palaeogeography Palaeoclimatology Palaeoecology, 337*, 130-142, doi: 10.1016/j.palaeo.2012.04.007.

Evans, M. E. (2012), Magnetostratigraphy of the Lodeve Basin, France: Implications for the Permo-Carboniferous reversed superchron and the geocentric axial dipole, *Studia Geophysica et Geodaetica, 56(3),* 725-734

Malinverno, A., J. Hildebrandt, M. Tominaga, and J. E. T. Channell (2012), M-sequence geomagnetic polarity time scale (MHTC12) that steadies global spreading rates and incorporates astrochronology constraints, *Journal of Geophysical Research-Solid Earth, 117(B06104)*, doi: 10.1029/2012jb009260.

Man, O., P. Pruner, and P. Schnabl (2012), The detection of common cycles in magnetic susceptibility observed in distant magnetostratigraphic sections, *Studia Geophysica et Geodaetica, 56(3),* 735-750

Mochales, T., A. Barnolas, E. L. Pueyo, J. Serra-Kiel, A. M. Casas, J. M. Samso, J. Ramajo, and J. Sanjuan (2012), Chronostratigraphy of the Boltana anticline and the Ainsa Basin (southern Pyrenees), *Geological Society of America Bulletin, 124(7-8)*, 1229-1250

Storme, J. Y., X. Devleeschouwer, J. Schnyder, G. Cambier, J. I. Baceta, V. Pujalte, A. Di Matteo, P. Iacumin, and J. Yans (2012), The Palaeocene/Eocene boundary section at Zumaia (Basque-Cantabric Basin) revisited: new insights from high-resolution magnetic susceptibility and carbon isotope chemostratigraphy on organic matter (d13Corg), *Terra Nova, 24(4)*, 310-317

Tauxe, L., et al. (2012), Chronostratigraphic framework for the IODP Expedition 318 cores from the Wilkes Land Margin: Constraints for paleoceanographic reconstruction, *Paleoceanography, 27(Pa2214)*, doi: 10.1029/2012pa002308.

Zhang, W. L., E. Appel, X. M. Fang, C. H. Song, and O. Cirpka (2012), Magnetostratigraphy of deep drilling core SG-1 in the western Qaidam Basin (NE Tibetan Plateau) and its tectonic implications, *Quaternary Research, 78(1)*, 139-148

Other

Igel, J., H. Preetz, and S. Altfelder (2012), Magnetic viscosity of tropical soils: classification and prediction as an aid for landmine detection, *Geophysical Journal International, 190(2)*, 843-855

Liu, H., D. Bedau, J. Z. Sun, S. Mangin, E. E. Fullerton, J. A. Katine, and A. D. Kent (2012), Time-resolved magnetic relaxation of a nanomagnet on subnanosecond time scales, *Physical Review B, 85(220405)*, doi: 10.1103/PhysRevB.85.220405..

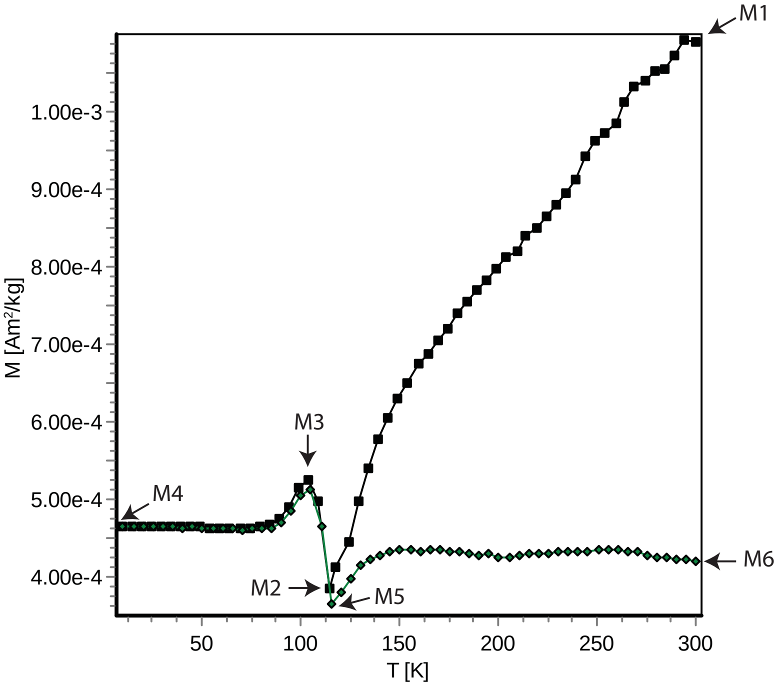
Lurcock, P. C., and G. S. Wilson (2012), PuffinPlot: A versatile, user-friendly program for paleomagnetic analysis, *Geochemistry Geophysics Geosystems, 13(Q06z45)*, doi: 10.1029/2012gc004098..

Ranjbar, M., S. N. Piramanayagam, R. Sbiaa, T. C. Chong, and I. Okamoto (2012), Advanced Magnetic Force Microscopy for High Resolution Magnetic Imaging, *Nanoscience and Nanotechnology Letters, 4(6),* 628-633

Fig 1. Anatomy of a low-T cycle of RTSIRM (initial magnetization M1). Black squares show cooling curve reaching a minimum (M2) at or near Tv, followed by an increase to a local maximum M3 and subsequent decline to M4 at the minimum temperature (in this case 10 K). On rewarming (green diamonds) the path retraces the cooling curve through M3 and M2 and reaches a slightly lower minimum (M5) before recovering somewhat on returning to M6 at room temperature. (unpublished data from P Kelso, granite from the Idaho Batholith)

Note that not all of these features are generally seen in RTSIRM low-T cycles; for many/most natural magnetites, M5≈M4≈M3≈M2.

Many parameters have been introduced to describe behavior during such experiments. The simplest is often called the "memory ratio," equal to M6/M1, i.e., the proportion of initial remanence that survives the low-T cycle (e.g., Dunlop & Argyle, 1991; Muxworthy & Williams, 2006). This can be determined without measurements at low T, and is therefore readily quantified. The same quantity is called 'second memory' by Özdemir et al (2002), to distinguish it from from 'first memory' (=M4/M1), the proportion of RTSIRM that survives the first crossing of the transition. King & Williams (2000) define "memory" as the magnetization recovered on rewarming through the transition, i.e., M6-M5. For cases where there is a distinct jump in remanence on crossing the transition, the parameter Δ_{VJ} (Muxworthy et al, 2003) is defined as size of the discontinuity, normalized to the initial remanence, i.e., Δ_{VJ} =(M3-M2)/M1; it can have positive values (as in the figure) or negative values. Other parameters known as ΔM_m and ΔM_c (Özdemir & Dunlop 2010) respectively denote magnetization differences in the monoclinic and cubic phases: ΔM_m = M4-M5, and ΔM_c = M1-M6.



transitional phenomena themselves. In particular, for many years there was no clear evidence to show the relative importance of the magnetocrystalline anisotropy transition and the Verwey transition in low-temperature demagnetization (Halgedahl & Jarrard 1995; Özdemir & Dunlop, 1999; Dunlop, 2003, Liu & Yu, 2004).

Three notable properties of magnetite's LTD behavior were noted almost immediately (e.g., Ozima et al., 1964; Kobayashi & Fuller, 1968; Merrill, 1970): (1) multidomain grains are demagnetized much more effectively than single-domain grains; (2) strong-field remanence is erased to a much greater extent than weak-field remanence (such as TRM); and (3) multiple low-T cycles generally demagnetize more completely than a single cycle. Kobayashi & Fuller (1968) speculated that the origin of "memory" (the remanence that survives LTD) is related to the origin of TRM.

Ozima et al (1964) showed experimentally that soft (1-10 mT) isothermal remanent magnetizations (IRMs), superposed on TRM or NRM, could be preferentially removed by low-temperature zero-field treatments. Yama-ai[*] et al (1963) observed a phenomenon that we have never seen reproduced, namely a reversal of magnetization in a single crystal on cooling through 130 K, followed by a return to the original polarity on rewarming (fig 2), and they hypothesized a mechanism involving two sources of magnetization, weakly coupled magnetostatically, since the self-reversal could be suppressed by application of a weak field during cooling. Kobayashi & Fuller (1968) carried out several experiments to test this idea further, including (a) comparison of room-T AF demagnetization spectra of RTSIRM and of "memory" after LTD, showing that the latter has much higher stability, and (b) superposition onto a room-T SIRM of a soft reverse-polarity low-T IRM, showing that "memory" is independent of the soft low-T overprint. They argued that a magnetostatic model could not explain these observations and that internal stresses must play a key role.

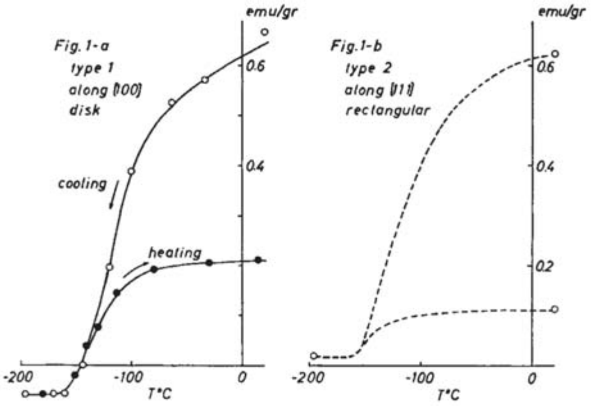


Fig 2. Yama-ai et al, Nature 1963; note self reversal along [100].

Effects of Domain State

Single Domain, low-T cycling of RTSIRM

In an SD particle at T > T_V, magnetic remanence lies along a minimum-energy orientation between one of the cubic <111> easy axes and the axis of particle elongation; the precise orientation depends on the relative strengths of the magnetocrystalline anisotropy and the shape anisotropy, the latter usually being stronger. On cooling through the isotropic point at T_K=130K, the cube edge orientations <100> become the magnetocrystalline easy axes, and then with the crystallographic change at T_V=120K, the monoclinic c-axis [001] becomes the strongly-preferred

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[*] Mituko Yama-ai married Minoru Ozima and her later papers are written as Mituko Ozima

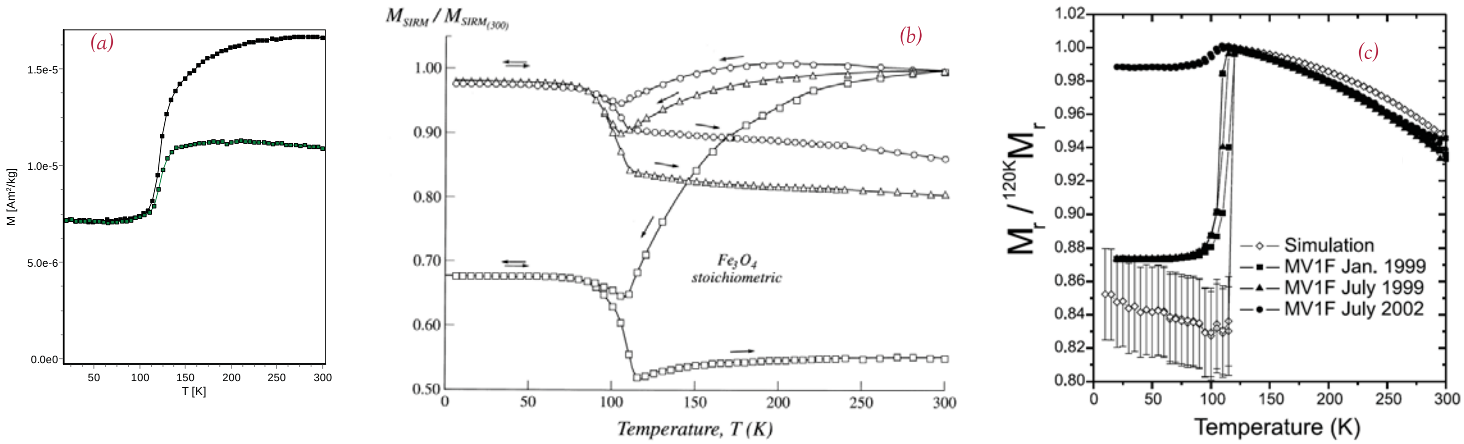

Fig 3. LTD of RTSIRM for samples containing SD magnetites. (a) silicate crystals from the Bushveld Complex with exsolved magnetite (Josh Feinberg, unpublished data). 'First memory' ≈ 50%; 'second memory' ≈75%; $\Delta_{VJ} \approx 0$. (b) synthetic submicron nearly-stoichiometric magnetite (circles, triangles and squares indicate respective sizes of 37, 100 and 220 nm; magnetites were grown from solution and have low stress and very little shape anisotropy). From Özdemir et al 2002. 'First memory' ranges from 68% to 98%; 'second memory' from 55% to 85%; both decrease with increasing grain size; Δ_{VJ} is larger on rewarming than on cooling. (c) samples of magnetotactic bacteria containing chains of SD magnetite (squares and triangles show measurements on freshly-cultured samples; circles show measurements after oxidation due to storage in air for three years). For the stoichiometric samples 'first memory' ≈ 94%; 'second memory' ≈100% as the curves are almost perfectly reversible; from Carter-Stiglitz et al (2004).

orientation of magnetization, regardless of grain shape. It has been commonly thought that in the absence of an applied field or magnetostatic interactions, one of the cube edge orientations is chosen at random to become the monoclinic c-axis. Rotation of the individual particle moments into c-axis alignment causes a loss of room temperature remanence, as some of the magnetization is effectively randomized (e.g. Fig. 3a,b,c). If there is no systematic relationship between crystallography and grain shape, the change from one uniaxial anisotropy to another results in a decrease of up to 50% in the net remanence of a population of grains.

When the sample is reheated, the moments might be expected to rotate reversibly back to their original direction with little to no loss of the original remanence . This appears to be true for some samples dominated by SD shape anisotropy at $T > T_V$ (e.g., Fig 3c), because there are only two easy axes to choose from on re-heating; the shortest rotation path will almost always be a return to the starting room-temperature direction. Perfect reversibility is rarely seen in nature, however, and for particles with small degrees of elongation (<1.15) it has been argued (Muxworthy and Williams, 2006) that cubic anisotropy indeed plays a role at $T > T_V$: the moment will find some orientation that is a local minimum in the sum of magnetocrystalline anisotropy energy (3 easy axes below T_K and 4 above) and magnetostatic (shape anisotropy) energy (2 or more easy directions). Not all of the individual particle moments return to their original orientations, and therefore there is incomplete recovery of remanence. This was demonstrated experimentally as early as 1978 when Levi and Merrill (1978) measured TRM remanence before and after cycling to T < 130K. They found that remanence recovery was greater in acicular grains than in equant grains. Likewise, interparticle magnetostatic interactions have been modeled to have a similar effect (Muxworthy and Williams, 2006), and can additionally reproduce intriguing features such as an additional decrease in M (rather than recovery) on warming back through T_V (Fig 3b).

Multi-domain, low-T cycling of RTSIRM

In contrast to the SD case, remanence within the domains of larger particles almost always lies along one of the cubic <111> axes for $T > T_K$. On cooling, the magnetocrystalline anisotropy energy decreases and domains reorganize irreversibly even at temperatures well above T_K (Halgedahl & Jarrard 95; Dunlop 2003; Liu and Yu 2004). For true MD populations (20 um and larger), 80% or more of RTSIRM can be erased by cooling to temperatures approaching but not reaching T_K. On cooling through the isotropic point, the cubic magnetocrystalline easy axes change to <100>. Instead of coherent rotation of magnetization as in the SD case, the room-temperature domain configurations become unstable and walls may begin to move or dissolve, while new walls are nucleated. However in the temperature interval between T_K and T_V, the magnetocrystalline anisotropy remains weak, and only rarely is there a direct visible indication of T_K in remanence cooling curves (Fig 4; Özdemir & Dunlop, 1999). Similarly, Kasama et al (2012) saw no significant changes in domain arrangements in images obtained by Lorentz microscopy above and below T_K.

It is at T_V, with a tenfold increase in magnetocrystalline anisotropy and a change from cubic to monoclinic symmetry, that domain reorganization is most forcefully driven. MD grains are large enough for the monoclinic phase to nucleate and begin growing in multiple regions independently of one another, with c-axis selection determined (in zero applied field) either randomly, or by local stress fields, or by inheritance of the cubic-phase domain-moment orientations. Kasama et al (2012) observed strong similarities in the domain configurations above T_V and below it after cooling in zero field, indicating some control of the monoclinic c-axis selection by the pre-existing local magnetization (as suggested by Bickford

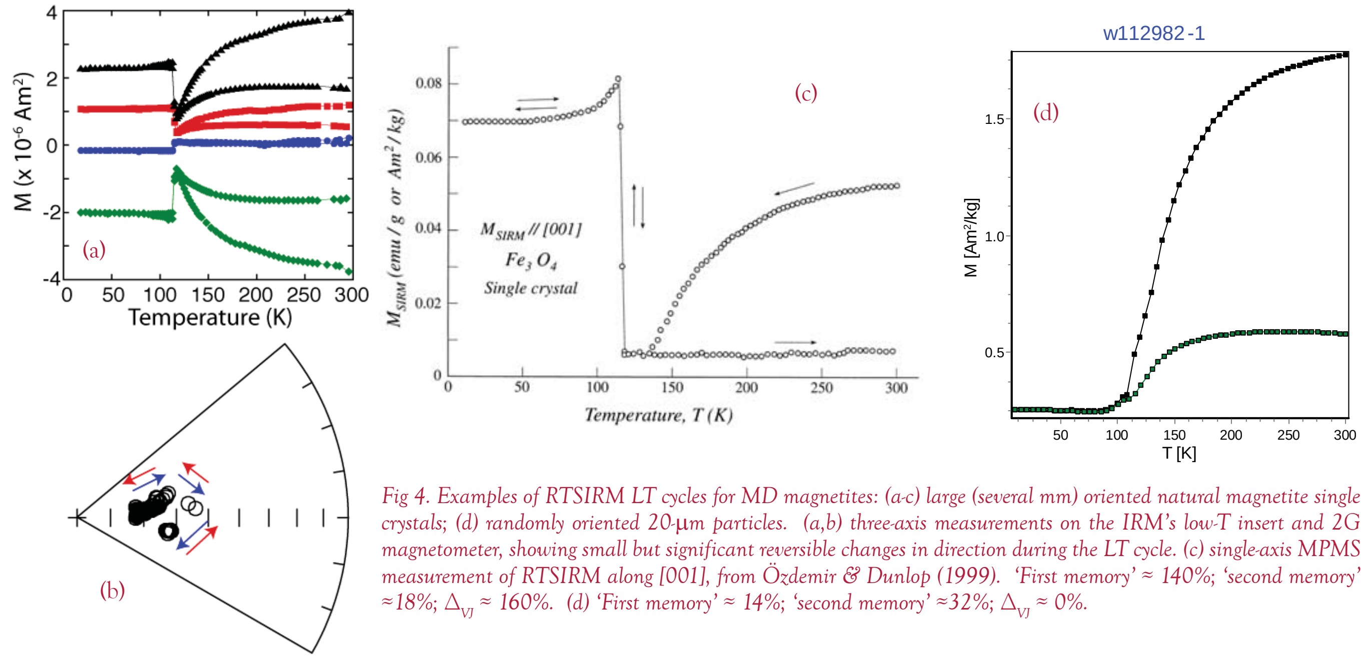

Fig 4. Examples of RTSIRM LT cycles for MD magnetites: (a-c) large (several mm) oriented natural magnetite single crystals; (d) randomly oriented 20-µm particles. (a,b) three-axis measurements on the IRM's low-T insert and 2G magnetometer, showing small but significant reversible changes in direction during the LT cycle. (c) single-axis MPMS measurement of RTSIRM along [001], from Özdemir & Dunlop (1999). 'First memory' ≈ 140%; 'second memory' ≈18%; Δ_{VJ} ≈ 160%. (d) 'First memory' ≈ 14%; 'second memory' ≈32%; Δ_{VJ} ≈ 0%.

in 1953). For samples containing large MD grains, and especially for single crystals, the remanence often "jumps" on cooling through T_V in zero field (Özdemir & Dunlop, 1999; Muxworthy et al., 2003; see also *IRMQ v19* n4); the magnitude of the increase depends on the nature of the initial remanence as well as on particle size. Changes in remanent magnetization on cooling and rewarming below T_V are almost always slight and perfectly reversible.

As the sample is warmed back through T_V, the strong monoclinic anisotropy abruptly vanishes, as does the monoclinic twinning, and domain walls will again unpin and reform. The c axis of each monoclinic twin domain becomes one of the cubic <100> easy axes, so there is no moment rotation required by the change in magnetocrystalline anisotropy, but its diminished strength shifts the balance towards shape and magnetoelastic anisotropies. It is interesting that any "jump" in remanence associated with T_V is generally almost perfectly reversible, i.e., M5~M2 (Fig 4).

On continued warming through T_K, the K1 anisotropy constant again changes sign and the cubic body diagonals again become the magnetocrystalline easy axes. There is no reason for the domains to reform precisely in the original room-T configuration, but Kasama et al (2012) have observed significant similarities in the patterns at 143 K before and after zero-field cycling through T_V. Nevertheless, in MD magnetites there is typically little or no recovery of the remanence lost on cooling. The "memory ratio" (M6/M1) decreases systematically with increasing grain size from SD through MD grain sizes (Merrill, 1970; Levi and Merrill, 1978; Heider et al., 1992). Halgedahl and Jarrard (1995) found a nearly linear relationship between the memory ratio and the logarithm of grain size and, therefore, the number of domains.

It has frequently been suggested that this memory ratio can therefore be used to estimate grain size, but such an interpretation is predicated on the assumption of stoichiometric magnetite. This cannot be assumed in many natural samples which will frequently have at least a small degree of cation deficiency or cation-substitution, both of which can have a strong affect on the memory ratio. Moreover the memory ratio in natural materials with mixed mineralogy depends on the relative proportions of phases that are invulnerable to LTD, and so granulometric estimation is inseparable from the more general unmixing problem. Additionally, as noted above, in the SD/PSD grain size region, acicular magnetite is found to have a higher memory ratio than comparably-sized equant grains.

A final complication in the interpretation of MD LTD memory lies in crystal defects and associated stress fields, which may serve as barriers to domain wall motion or as sites for wall re-nucleation, and which may thereby help to transfer magnetically-stored information back and forth between the cubic and monoclinic phases (Kobayashi and Fuller, 1968; Hodych, 1991; Heider et al 1992; Hodych et al., 1998; Kasama et al., 2012). Thus, the memory is a function of not only grain size but also stoichiometry and defects/stresses, which we will return to in future articles. Because LTD memory depends on these factors, it is not surprising that it also depends on the nature of the initial remanence.

LTD of Different Remanences; Coercivity and Unblocking-temperature Spectra after LTD

Is it possible to isolate primary thermoremanence by selectively demagnetizing viscous and other overprints using LTD? Can the portion of NRM carried by MD grains be selectively removed by low-temperature treatments, leaving an ideal SD-carried remanence for paleointensity or paleothermometry studies? The answer to these is an unequivocal "Yes, to a certain extent, but..."

Interest in the use of LTD to isolate the primary TRM carried by SD grains has of course been particularly strong in connection with paleointensity, where only such ideal records are amenable to techniques such as the Thellier-Thellier method, which depend on the laws of pTRM additivity, independence and reciprocity. Many studies have shown that the remanent "memory" of TRM and pTRM (and their anhysteretic analogues) after LTD have more SD-like properties than the untreated thermoremanences, including closer adherence to the virtuous properties of additivity, independence and reciprocity, but LTD pretreatments still commonly fail to yield reliable paleointensities from samples with MD magnetite (Dunlop & Argyle, 1991; Heider et al, 1992; McClelland et al., 1996; Shcherbakova et al., 1996; Muxworthy, 2000; Muxworthy & McClelland 2000a,b; Yu et al 2003; Yamamoto et al 2003; Borradaile et al., 2004; Dunlop et al., 2005).

Multicycle LTD

Erasure of magnetic information by a single cycle through T_V is imperfect; some fraction is remembered in spite of the randomness inherent in phase nucleation, c-axis selection, domain nucleation, etc. Liu and Yu (2004) found experimentally that remanence decays exponentially with the number of LTD cycles, to a nonzero level that depends on the temperature endpoints of the LTD cycles, as well as on all the usual other factors like particle size and type of remanence. The first cycle is responsible for more than 75% of the total remanence loss caused by 10 or more LTD cycles, when the cycles cross T_K but not T_V. For lower-temperature cycles that cross T_V but not T_K, the first cycle accounts for about half the total demagnetization accomplished by 10 or more cycles. Liu and Yu (2004) modeled the process using a "Boltzman-analog" approach involving both domain reorganization above T_K and easy-axis reorientation through T_K and T_V.

Experimental Artifacts

No article on the fine details of low-temperature magnetic behavior would be complete without some mention of various nefarious experimental artifacts that torment and bedevil us on a regular basis, by mimicking and/or distorting the signatures of the Verwey transition and other significant features. In the context of LTD, the most bothersome issue involves spurious abrupt decreases in remanence while cooling in zero field, due to reorientation of particles in powder samples or other similar effects. Typically these appear as discontinuous steps superposed on a smoothly changing signal (e.g., Fig 5). With surprising frequency the anomalous drops occur within the temperature ranges where we look for the Morin transition (hematite), the Verwey transition, the Besnus transition (pyhrrotite), or different mineral isotropic points, and it can be difficult to evaluate their significance. Repeat runs commonly show that they are not reproducible in detail, or often even in gross form; repacking the sample more tightly to immobilize the particles more completely in many cases eliminates the artifacts. It is conceivable that particle reorientation is itself related in some way to the phase transitions, and the abrupt drops may still in some cases be a guide to the presence of transitions. However, in order to obtain unambiguously interpretable results we recommend, when practical, working with solid rock chips/slices, or mixing granular materials with a compressible binder to reduce or eliminate the occurrence of such gremlins.

Closing Remarks

In the nearly fifty years that have passed since the first work on LTD, it has continued to draw interest and stimulate research, even if it has not quite become a staple of paleomagnetism in the same way that thermal and alternating-field demagnetization methods are. Stepwise LTD (e.g. Dunlop 2003) and full 3-axis magnetization measurements during low-T cycles (Bowles et al, 2010; Smirnov & Tarduno, 2011) promise to improve our understanding of natural and artificial remanences carried by magnetite, and direct imaging of cubic and monoclinic crystallographic and magnetic microstructure (Kasama et al., 2012) will continue to clarify their interdependent changes across T_V, deepening our understanding of transition-related phenomena as well as of the stabilizing mechanisms of room-temperature remanence. Behavior of room-T remanence during LTD provides information on the mineralogy, grain sizes, stoichiometry and anisotropy of the carriers, and for these reasons magnetization measurements across low-temperature transitions have become, and will continue to be, essential for studying the sources (minerals and mechanisms) of stable remanence in natural materials.

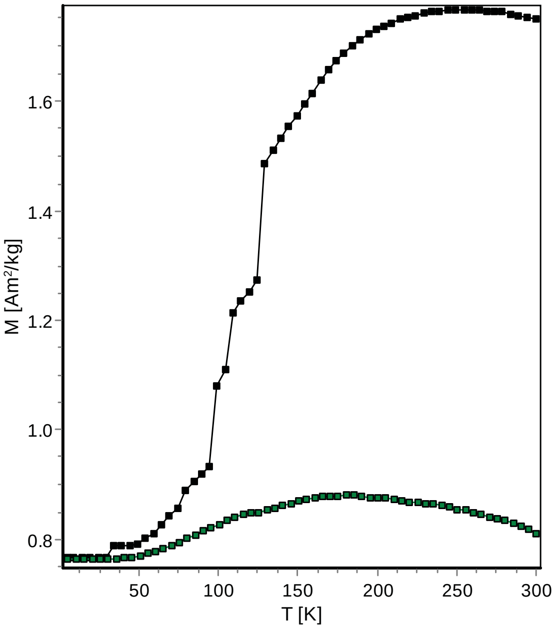

Fig. 5. Frustrating inexplicable mystery discontinuities commonly found in cooling curves on powder samples, often tantalizingly close to significant transition temperatures. Repacking and remeasuring sometimes eliminates these.

References

Bickford, L. R., Jr. (1953), The low temperature transformation in ferrites, Rev. Mod. Phys., 25, 75–79

Borradaile, G. J., K. Lucas, and R. S. Middleton (2004), Low-temperature demagnetization isolates stable magnetic vector components in magnetite-bearing diabase, Geophys. J. Int., 157(2), 526-536

Bowles, J.A., P. A. Solheid, M. Jackson, J. Feinberg, and B. Moskowitz (2010), New Low-Temp Probe for 3-Axis Magnetic Measurements, IRM Quarterly, 19(4).

Carter-Stiglitz, B., B. Moskowitz, and M. Jackson (2004), More on the low-temperature magnetism of stable single domain magnetite: Reversibility and non-stoichiometry, Geophys. Res. Lett., 31(6), 1-5

Dunlop, D. J. (2003), Stepwise and continuous low-temperature demagnetization, Geophys. Res. Lett., 30(11), doi:10.1029/2003GL017268

Dunlop, D. J., and K. S. Argyle (1991), Separating multidomain and single-domain-like remanences in pseudo-single-domain magnetites (215–540 nm) by low-temperature demagnetization, J. Geophys. Res. B, 96, 2007–2017

Dunlop, D. J., B. X. Zhang, and Ö. Özdemir (2005), Linear and nonlinear Thellier paleointensity behavior of natural minerals - art. no. B01103, J Geophys Res-Sol Ea, 110(B1)

Flanders, P. J., and W. D. Doyle (1962), Motor Driven Magnetometer for Thin Magnetic Films, Rev. Sci. Instr., 33(6), 691-693, doi: 10.1063/1.1746667.

Halgedahl, S. L., and R. D. Jarrard (1995), Low-temperature behavior of single-domain through multidomain magnetite, Earth Planet. Sci. Lett., 130, 127–139

Hartstra, R. L. (1983), TRM, ARM, and Isr of two natural magnetites of MD and PSD grain size, Geophys. J. R. Astr. Soc., 73, 719–737

Heider, F., D. J. Dunlop, and H. C. Soffel (1992), Low-temperature and alternating field demagnetization of saturation remanence and thermoremanence in magnetite grains (0.37 µm to 5 mm), J. Geophys. Res. B, 97, 9371–9381

Hodych, J. P. (1991), Low-temperature demagnetization of saturation remanence in rocks bearing multidomain magnetite, Phys. Earth Planet. Inter., 66, 144–152

Hodych, J. P., R. I. Mackay, and G. M. English (1998), Low-temperature demagnetization of saturation remanence in magnetite-bearing dolerites of high coercivity, Geophys. J. Int., 132(2), 401-411

Kasama, T., R. J. Harrison, N. S. Church, M. Nagao, J. M. Feinberg, and R. E. Dunin-Borkowski (2012), Ferrimagnetic/ferroelastic domain interactions in magnetite below the Verwey transition. Part 1: Electron Holography and Lorentz Microscopy, Phase Transitions: A Multinational Journal, doi: 10.1080/01411594.2012.695373.

Kobayashi, K., and M. Fuller (1968), Stable remanence and memory of multi-domain materials with special reference to magnetite, Phil. Mag., 18, 153, 601-624.

King, J.G., and W. Williams (2000), Low-temperature magnetic properties of magnetite, J. Geophys. Res. 105 16427-16436.

Levi, S., and R. T. Merrill (1978), Properties of single domain, pseudo-single domain, and multidomain magnetite, J. Geophys. Res. B, 83, 309–323

Liu, Q. S., and Y. J. Yu (2004), Multi-cycle low-temperature demagnetization (LTD) of multidomain Fe3O4 (magnetite), Journal of Magnetism & Magnetic Materials, 283(2-3), 150-156

Merrill, R. T. (1970), Low-temperature treatments of magnetite and magnetite-bearing rocks, J. Geophys. Res., 75, 3343–3349

McClelland, E., A. R. Muxworthy, and R. M. Thomas (1996), Magnetic properties of the stable fraction of remanence in large multidomain (MD) magnetite grains: single-domain or MD?, Geophys. Res. Lett., 23(20), 2831-2834

Muxworthy, A. R. (2000), Cooling behaviour of partial thermoremanences induced in multidomain magnetite, Earth Planet. Sci. Lett., 184, 149-159

Muxworthy, A. R., and E. McClelland (2000a), Review of the low-temperature magnetic properties of magnetite from a rock magnetic perspective, Geophys. J. Int., 140(1), 101-114

Muxworthy, A. R., and E. McClelland (2000b), The causes of low-temperature demagnetization of remanence in multidomain magnetite, Geophys. J. Int., 140(1), 115-131

Muxworthy, A. R., and W. Williams (2006), Low-temperature cooling behavior of single-domain magnetite: Forcing of the crystallographic axes and interactions, J Geophys Res-Sol Ea, 111(B07103), doi: 10.1029/2006JB004298.

Muxworthy, A. R., D. J. Dunlop, and Ö.Özdemir (2003), Low-temperature cycling of isothermal and anhysteretic remanence: microcoercivity and magnetic memory, Earth Planet. Sci. Lett, 205, 173-184

Özdemir, Ö., and D. J. Dunlop (1999), Low-temperature properties of a single crystal of magnetite oriented along principal magnetic axes, Earth and Planetary Science Letters, 165(2), 229-239

Özdemir, Ö., and D. J. Dunlop (2010), Hallmarks of maghemitization in low-temperature remanence cycling of partially oxidized magnetite nanoparticles, J. Geophys. Res., 115(B2), B02101, doi: 10.1029/2009jb006756.

Özdemir, Ö., D. Dunlop, and B. M. Moskowitz (2002), Changes in remanence, coercivity and domain state at low temperature in magnetite, Earth Planet. Sci. Lett., 194(3-4), 343-358

Ozima, M., M. Ozima, and T. Nagata (1964), Low temperature treatment as an effective means of "magnetic cleaning" of natural remanent magnetization, J. Geomagn. Geoelectr., 16, 37-

Shcherbakova, V. V., V. P. Shcherbakov, P. W. Schmidt, and M. Prévot (1996), On the effect of low-temperature demagnetization on TRMs and pTRMs, Geophys. J. Int., 127(2), 379-386

Smirnov, A. V., and J. A. Tarduno (2011), Development of a low-temperature insert for the measurement of remanent magnetization direction using superconducting quantum interference device rock magnetometers, Geochem. Geophys. Geosyst., 12(4), Q04Z23, doi: 10.1029/2011gc003517.

Syono, Y. (1965), Magnetocrystalline anisotropy and magnetostriction of Fe3O4–Fe2TiO4 series, with special application to rock magnetism, Jpn. J. Geophys., 4, 71–143

Yama-ai, M., M. Ozima, and T. Nagata (1963), Self-reversal of remanent magnetization of magnetite at low temperature, Nature, 198, 1188-1189.

Yamamoto, Y., H. Tsunakawa, and H. Shibuya (2003), Palaeointensity study of the Hawaiian 1960 lava: implications for possible causes of erroneously high intensities, Geophys. J. Int., 153(1), 263-276

Yu, Y., D. J. Dunlop, and Ö. Özdemir (2003), Effect of low-temperature treatments on pseudo-Thellier paleointensity determination, J. Geophys. Res., 108(B4), doi:10.1029/2002JB002138

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